Superconducting Accelerator Cavities on a Large Scale

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Abstract

Large-scale construction of superconducting accelerator cavities is now in progress at several laboratories around the world. KEK has completed thirty-two 5-cell niobium 508 MHz cavities for TRISTAN in the autumn of 1989 and has an operating experience of many thousands hours with electron and positron beams. CEBAF, CERN and DESY are also building superconducting cavities on a large scale and they are supposed to start operation in the near future. Some other laboratories are building or intending to build accelerators for nuclear physics or free electron lasers using superconducting cavities. Superconducting cavities are also considered to be used in the accelerators for B-factory or linear colliders. An overview of these projects is described, some of the problems associated with large-scale cavity production are discussed.

I. INTRODUCTION

The first acceleration of electrons by a superconducting structure was carried out at Stanford in the middle of 1960's[1]. This was followed by the start of a project of HEPL 2 GeV superconducting linac[2] anticipating quite an attractive continuous electron beam of 100 μA. This linac consists of the L-band niobium structure operating at the temperature of 1.9 K, very similar in frequency and temperature to the CEBAF accelerator[3] now being built. The HEPL superconducting linac was the first large-scale project using superconducting cavities. Though it did not complete the original design goal, still it has greatly contributed to demonstrating[4] the superiority of superconducting RF accelerators and how useful they are, as well as in developing the technique for niobium cavities, subatmospheric cryogenics and many other techniques important for superconducting RF accelerators. Many people have grown up from the HEPL SC-RF project and they are now playing important roles in the superconducting RF business.

During 1970's, superconducting cavities came to be noticed[5] as a useful tool to accelerate electrons or positrons in large colliding ring machines in which the considerable amount of synchrotron losses are too costy to make up with normal conducting cavities. Demands for the superconducting cavities in the colliding ring application have pushed the R&D of radio-frequency superconductivity. To understand the mechanisms which limit the accelerating field gradient and the Q of superconducting cavities, much effort has been devoted at the various laboratories. The major progress accomplished in these ~ 15 years include the following:

a) Appropriate shaping of cavity geometry to avoid electron multipacting. This was proved to be effective both theoretically[6] and experimentaly[7].

b) Improvement of the thermal conductivity of the cavity material to pushing the field limit[8] that results from thermal instability. Existence and location of "defects" on the cavity wall, which in many cases causes the thermal instability, are shown clearly by the beautiful thermometry[9].

c) Reduction of field emission electrons by improved surface treatment and clean handling[10]. Extensive R&D in this direction are still going on[11][12].

As a result of these efforts, accelerating field gradient of ~ 5 MV/m became "standard" for the design value of niobium cavities for high-ß structures, while 10 ~ 15 MV/m is being taken for the near-future planning. For instance, the value is 10 MV/m for the B-factory at Cornell[13], 15 MV/m for the first stage of the TESLA proposal[14] and 12.5 MV/m for the PILAC at Los Alamos[15].

Recent experiments on niobium cavities at various laboratories frequently show the field gradient above 15 MV/m, such as the examples shown in Table 1.

Table 1
Recent experimental results on niobium cavities at various laboratories

Laboratory		Type of cavity	Field gradient
KEK	[16]	508 MHz, 5-cell	Eacc, 15 MV/m
CEBAF	[17]	1500 MHz, 5-cell	Eacc, 18 MV/m
Cornell	[18]	3 GHz, single cell	Epeak, 53 MV/m
Wuppertal	[19]	3 GHz, 9-cell	Eacc, 16 MV/m

The following is a brief review of large-scale electron accelerators using superconducting cavities already built or now being built and some problems accompanied with large-scale production of superconducting cavities are discussed. Details of the present status of each project will be presented elesewhere and are not discussed in this paper. Also low-ß structures for heavy ion acceleration is another important use of superconducting cavities but is not discussed here.

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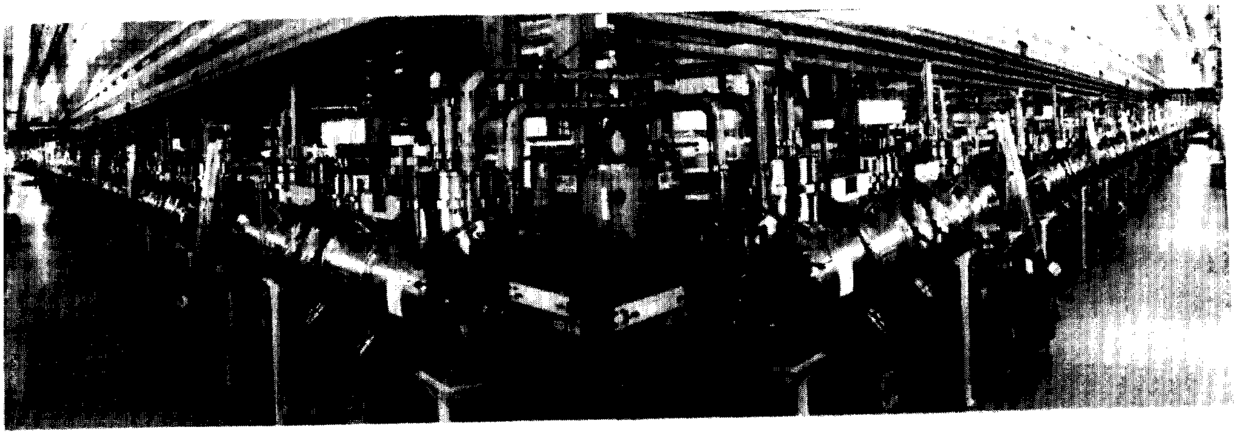

Fig. 1 Superconducting RF system of TRISTAN installed on both sides of the Nikko colliding point. The picture is synthesized from two photographs.

II. LARGE-SCALE PROJECTS USING SUPERCONDUCTING CAVITIES

TRISTAN

TRISTAN is the first e^+e^- storage ring equipped with an actual superconducting RF system operating on a large scale.

Sixteen 5-cell 508 MHz niobium cavities were installed in the summer of 1988 and sixteen more cavities were added one year later, in the summer of 1989[20][21]. The cavities have had operational experience with the beam for more than two and a half years. Except for several cavities which were damaged by input coupler leakage or other accidents, most of the cavities are keeping their performances without degradation during many thousands of hours of beam operation[22]. Figure 1 is a picture of the superconducting RF system of TRISTAN showing cryostats installed on both sides of the Nikko colliding point.

Averaged value of maximum accelerating field measured in the horizontal cryostats without beam has been kept unchanged at ~ 7 MV/m[23] from the beginning to the present. Soon after the early beam operation with superconducting cavities, it was found that the beam current had to be limited to 12 ~ 13 mA due to the unexpected overheating at coaxial lines and connectors of higher-mode couplers, and they have been replaced with modified coaxial lines and connectors with larger size during the autumn shutdown of 1990. Beam current of TRISTAN is at the moment not high enough due to other reasons so that the effectiveness of the modification has not yet been evaluated. Additional four cavities have been fabricated in 1990 and assembled in two cryostats as stand-by modules to replace old cavities with poor performance. At present, there is no plan to build more superconducting cavities for TRISTAN, as it is directed to operate in a high luminosity mode than to go up to a higher energy.

Fundamental R&D for the Nb cavities have been mainly done by KEK, although some aspects relating to the mechanical engineering for instance were developed in collaboration with the industry. There is no performance guarantee of the cavity in the contract and almost all of the manufacturing procedures were given by KEK. At many important steps during the manufacturing, person(s) from KEK have checked the cavities at the factory to decide whether or not go to the next step[24].

Assembly of the 5-cell cavities for the vertical test and assembly of the two 5-cell cavities inside the horizontal cryostat were done at KEK because a clear room facility was required. Mechanical tuning to get the uniform field distribution and the correct resonance frequency, as well as the vertical test and the horizontal test were carried out at KEK. All RF tests of cavities at room temperature and at liquid He temperature were performed at KEK.

The regulation concerning high pressure gas vessels is a particular problem in Japan. Complicated procedures to get the permission to build or modify the cavities or to get checked by the officer at many stages during the manufacturing process consumes much time and money.

LEP

About 200 of 4-cell 350 MHz cavities will be instaled in LEP to raise the beam energy beyond 90 GeV[25].

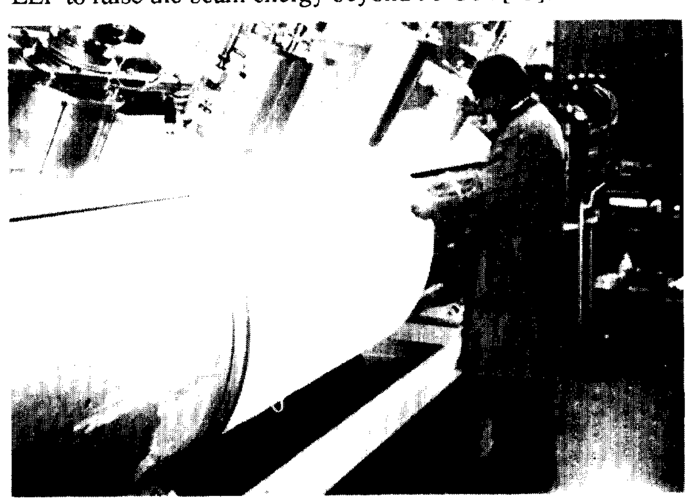

Fig. 2 Specially designed LEP cryostat being assembled.

By the end of this year 32 cavities (8 modules) will be installed providing the accelerating field of 272 MV[26], 3 modules are built in house, two of them are Nb/Cu cavities and one module Nb sheet cavity. The other 5 modules of Nb sheet cavities are produced by an outside company. Delivery has just started.

The remaining 168 Nb/Cu cavities will be produced during 1992 ~ 1993 by outside companies. Installation is expected to be completed by the beginning of 1994.

Specially designed demountable cryostats as shown in Figure 2, have the advantage of easy access to the cavities and accessaries. The technique of sputtering niobium to the inner surface of copper cavities have been successfully developed at CERN and the technique has been transferred to the industry. because the thermal conductivity of copper is better than niobium at low temperature, Nb/Cu cavities are expected not to suffered from the thermal instability caused by the surface defects. Also the benefit of inexpensive cost of Nb/Cu cavities is taken into consideration[27].

Each cavities will be vertically tested at CERN, final assembly is done at the companies. Horizontal tests of modules will be performed at CERN before installation.

HERA

A total of 16 niobium cavities of 500 MHz 4-cell structures will be installed in HERA in this May, half of them already installed. Additional 32 cavities might be ordered if the operating experience is positive[28]. Q-degradation due to hydrogen contamination in the niobium[29] is a severe problem for cavities made out of high purity niobium, DESY is trying different chemical process and has obtained sign of success.

Figure 3 shows cryostats of HERA installed in the tunnel.

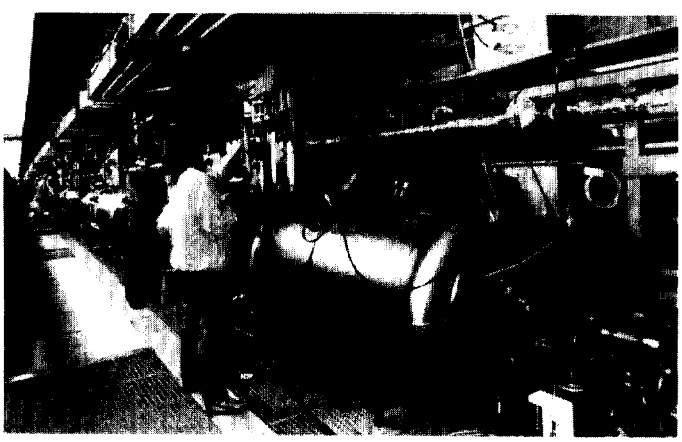

Fig. 3 Eight cryostats of superconducting cavities installed in the HERA tunnel.

CEBAF

330 cavities of 1500 MHz niobium 5-cell structure are on the way to production and testing. They will be installed by the end of June 1993. Each pair of cavities are kept under vacuum after initial assembly by means of the ceramic power windows and gate valves at each end of the pair. This sealing technique prevents a reduction in field gradient between the vertical pair tests and the horizontal cryomodule tests. Figure 4 shows the CEBAF cryomodule containing four pairs of 5-cell cavities.

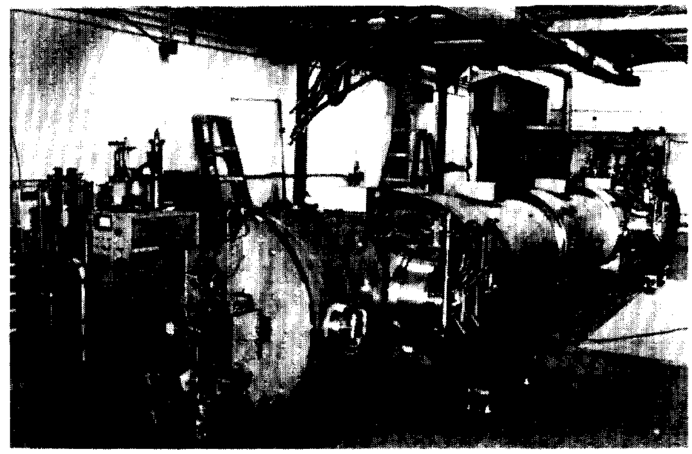

Fig. 4 CEBAF cryomodule containing four pairs of 5-cell.

S-DALINAC (Superconducting Darmstadt Linear Accelerator)

Superconducting 130 MeV electron linear accelerator at Darmstadt had the first beam in August 1987[30]. It consists of S-band cavities, 5-cell capture section plus two 20-cell sections for the injector and eight 20-cell sections for the main linac operating at 2 K. Two cavities in the main linac will be replaced with new ones with high RRR niobium to increase the energy gain. Figure 5 shows the main features of the S-DALINAC.

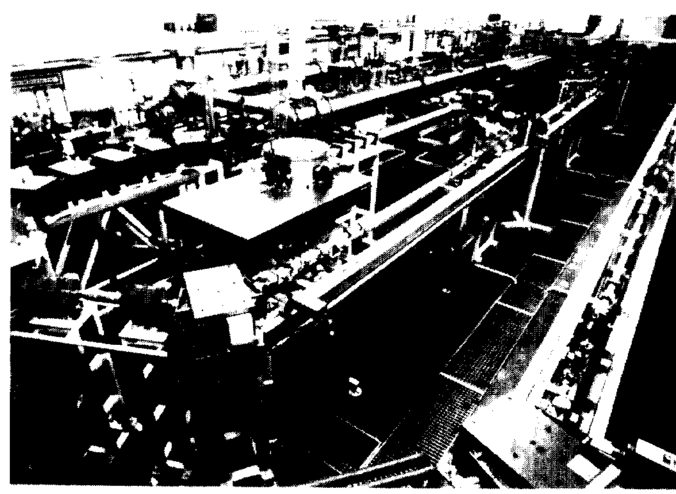

Fig. 5 The main features of the S-DALINAC.

III. PROBLEMS ASSOCIATED WITH A LARGE SCALE CAVITY PRODUCTION

Technological Transfer to Industry

Transfer of techniques from laboratory to industry becomes necessary during the course of transition, from small-scale development of a prototype to large-scale cavity production. Though manner and degree of technological transfer are different for each project, they are going rather smoothly. The important and common request for the industry are for them to understand the importance of cavity surface and necessity of cleanliness also to keep good workmanship.

The results of the first cool down for the single cell test cavity which was produced in a standard procedure developed at KEK for TRISTAN is compared in Figure 6 to the first 5-cell cavity which was built in the large-scale production scheme. It shows successful technological transfer from the small scale prototype to the large scale production.

Depending on the technical level of the company and also on the policy of each laboratory, frequency of the check during manufacturing by the laboratory staff is quite different in each cases. Checks are quite frequent for TRISTAN and HERA and very rare is for CEBAF.

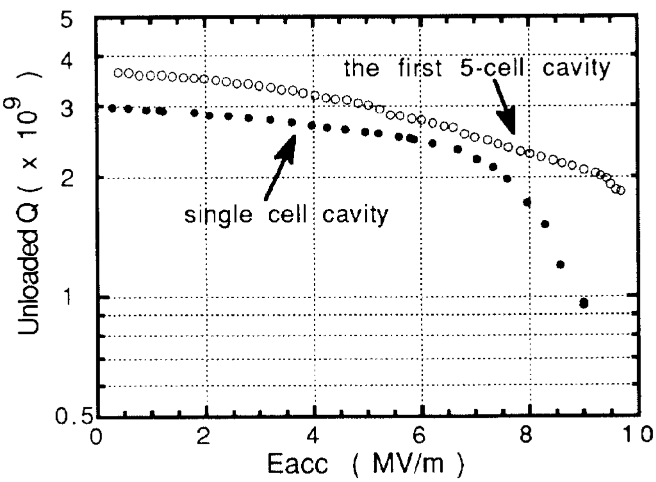

Fig. 6 Results of the first cool down tests for the single cell and the first 5-cell cavity of TRISTAN showing the technological transfer to the industry.

<u>Long Term Quality Control</u>

Quality control is needed over quite a long term. In the case of the TRISTAN cavities for instance, there were some problems on the quality control during production period of 32 cavities.

One of the problems was contamination of electro-polishing acid. It was for the first time investigated after the reduction of the threshold field for the electron emission[10] was noticed at the seventh 5-cell cavity. It was solved by cleaning the electro-polishing system and the intensified monitoring of acid contamination.

Another problem was in niobium production. The vendor was still trying to improve the purity of niobium and it caused a gradual increase of RRR during the manufacturing period[10]. It was good for the thermal conductivity of the cavity wall but it created another problem with the mechanical property of the cavity.

Heat treatment tests of niobium at various temperatures had to be repeated and annealing temperature of cavities after electro-polishing were determined for each lots of niobium to fulfil the required mechanical property of the cavities.

IV. PROSPECTS

Major effort is directed for raising the field limit in the superconducting cavities to decrease the field emission electrons. Thorough rinsing after chemical treatment and clean handling have contributed to the reduction of electron emission, vacuum heating is emerging as the next treatment.

Figure 7 is a plot of the RF voltage provided by the superconducting cavities (achieved or being built) at large-scale projects. A logarithmic increase of total voltage is seen and a point for the first stage of TESLA [14] is on the extension of the line.

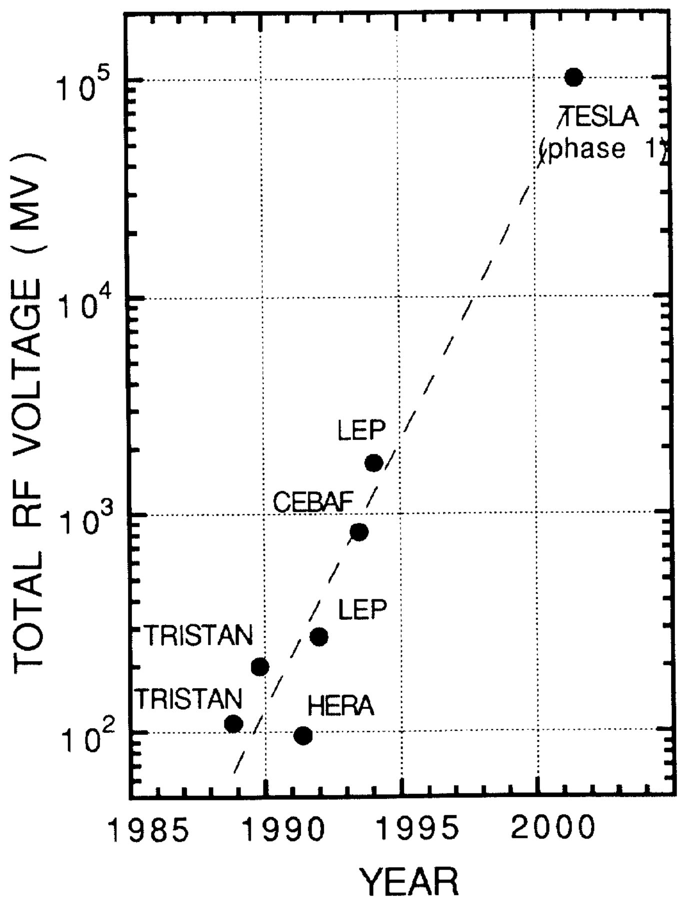

Fig. 7 Total RF voltage provided by superconducting cavities.

V. ACKNOWLEDGEMENT

The author wishes to thank his colleagues from CEBAF, CERN, Cornell, Darmstadt, DESY, KEK, Wuppertal for kindly suppling information for his review. Also he thanks to T. Furuya, K. Saito and N. Kako of KEK, H. Harada of

Mitsubishi Electric for useful discussions and preparing the manuscript.

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